N90-20808

CONTROL STRATEGIES FOR A TELEROBOT

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Abstract

One of the major issues impacting the utility of telerobotic systems for space is the development of effective control strategies. For near-term applications, telerobot control is likely to utilize teleoperation methodologies with integrated supervisory control capabilities to assist the operator. In this paper, two experiments are reported which evaluated two different approaches to telerobotic control: bilateral force reflecting master controllers and proportional rate six degrees of freedom (DOF) hand controllers. The first experiment compared the controllers on performance of single manipulator arm tasks. The second experiment required simultaneous operation of both manipulator arms and complex multiaxis slave arm movements. Task times were significantly longer and fewer errors were committed with the hand controllers. The hand controllers were also rated significantly higher in cognitive and manual control workload on the two-arm task. The master controllers were rated significantly higher in physical workload. The implications of these findings for space teleoperations and higher levels of control are discussed.

1. INTRODUCTION

Automation and robotics (A&R) will play an important role in future space activities such as satellite servicing and space station assembly and maintenance. Two characteristics of space operations make it well suited to an A&R technology. First, space is an extremely hostile environment. To safely work in space, the extravehicular activity (EVA) astronaut must don an extravehicular mobility unit (EMU), which greatly reduces his dexterity and ability to work. Second, human resources in space are extremely limited, and the dollar cost is high. In addition, missions that are dangerous, require immediate action, or can be performed at orbits not convenient to shuttle operations will require a robotics capability for safe and efficient operations.

Space offers a challenge to robotics technology. Few operations in space are routine. A robotic system must, therefore, be capable of handling tasks that are either unplanned or cannot be planned to an assembly-line level of detail, i.e., the system must be capable of real-time strategy modification.

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Given present technology limitations, these requirements are somewhat beyond the capability of fully automated systems. It is desirable, therefore, to include the "man-in-the-loop" to integrate his knowledge base and decision-making capabilities into system operations. Thus, near term space robotic systems are likely to be teleoperated as an intermediate step to supervisory control and full automation.

Rice et al. [1] identified three factors in space teleoperations limiting human integration with the system. Included were the provision of adequate visual feedback from the worksite, the development and selection of control devices, and the effect of communication time delays on performance. This study is directed toward the issue of control input devices. A wide variety of control devices are presently used for teleoperating ranging from point-by-point position switches to hand controllers to master replica arms. The selection of the system is often governed by the unique uses of the manipulator. In space applications, however, manipulators are intended to be used for a vast array of different functions. Hence the selection of control input devices is especially difficult.

Recent developments in hand controller technology have enabled the integration of all six DOF into a single compact controller. Concern has been voiced over the ability of the operator to precisely control six DOF with one hand [2]. Inadvertent cross-coupling of axes is expected to be much more likely with a six-DOF controller. Heartly et al. [3] reported a comparison of a six-DOF controller with two three-DOF controllers on several manipulator tasks. The six-DOF controller was found to be useful for tasks requiring single axis commands and where workload was very low. For high-workload tasks where multiaxis inputs were required, the three-DOF controllers were found to be superior. Six-DOF controllers have been found to more mentally demanding than three-DOF controllers [1]. However, in a study where three- and six-DOF controllers were directly compared for operating a simulated Shuttle Orbiter remote manipulator system, no differences were found between the controllers in performance errors for low workload docking tasks or high workload tracking tasks [4]. The purpose of the present study is to extend the research on six-DOF controllers to dexterous manipulators.

Two studies were conducted evaluating methods of controlling a dexterous telerobot. In the first study, tasks requiring only single-arm control (six-DOF tasks) were performed including a task board and a simulated satellite orbital replacement unit (ORU) removal and installation. In the second study a truss assembly task requiring simultaneous control of both arms (a 12-DOF task) was performed. The main objective was to compare two types of controllers: 1) bilateral-force-reflecting master-arm replica controllers based upon joint position control; and 2) six-DOF ball-shaped hand controllers based upon proportional resolved-rate control. Since forces were not reflected to the hand controllers, an audio signal was provided to the operator which changed in tone and pulse frequency as forces built-up in the slave arms.

2. STUDY 1

2.1 Methods

2.1.1 Participants - Six subjects having little experience operating dexterous manipulators participated.

2.1.2 Experimental Design - Two factors were investigated: (1) control system having two levels (master controller and six-DOF hand controller); (2) task scenario having two levels (task board and ORU changeout). The variables were orthogonally combined and varied within subject. For certain analyses, the change in performance over trials was examined too.

2.1.3 Laboratory and Test Equipment - The study was conducted in Grumman's Telerobotics Development Laboratory. The facility was divided into a remote worksite, the telerobot systems and test articles in one area while the operator workstation, including all controls and displays, were located in another area. Direct visual contact with the worksite was prevented by a curtain.

The telerobot system consisted of a Teleoperator Systems Corporation SM-229 master-slave manipulator with Oak Ridge National Laboratory electronics and is owned by the Princeton Plasma Physics Laboratory. It was a bilateral-force-reflecting system with two six-DOF slave arms, plus one-DOF end effector. Each arm was capable of shoulder roll ($\pm$ 45°) and pitch ($\pm$ 90°), elbow pitch (+ 160°/50°) and yaw ($\pm$ 180°), and wrist roll (360°) and pitch (+ 45°/-120°).

Four CCTV cameras were used to relay visual information from the worksite to the operator's workstation. Two cameras were located to provide views from approximately 45° right and left of the manipulator. This camera was positioned approximately 0.76 m above the manipulator arms. The fourth camera was also located between the manipulator slave arms, but was positioned approximately 1.8 m above the arms. While the first three cameras could be controlled with pan, tilt, iris, and zoom functions, pan and tilt were not available for the fourth camera.

The workstation was designed from concepts developed for a generic workstation for the Space Station. The workstation was 211 cm high, 171 cm wide, divided into center, left, and right modules. The left and right modules were rotated 30° toward the center module. The center module housed a 48 cm low resolution CCTV monitor and the right module housed two 20 cm monitors. All camera controls were located on a panel to the left of the workstation. Since only three views of the worksite could be displayed at one time, the camera console provided a camera select function for choosing which camera views were presented.

The master controller was a full-scale replica of the slave arm. Control was achieved through position control loops for each DOF. The operator positioned the master arm to the desired configuration creating a position error between the master and slave. Motors in the salve arm drove it until the position error was zero. When zero position error could not be attained, force was reflected to the master arm. The grippers were closed and opened by squeezing the hand grip.

The six-DOF hand controllers were developed by CAE Electronics, Ltd. They provided bidirectional resolved rate control of the X, Y, and Z axes and roll, pitch, and yaw. Voltage outputs from the controllers were proportional to the displacement of the hand gripper ball and were transformed by computer to an end effector displacement vector (direction and velocity). All slave arm joint angles and velocities required to implement a control input were resolved in software. The spherical gripper ball was approximately 7.35 cm in diameter.

A fin was vertically positioned along the forward side of the ball to facilitate hand grip. The slave ar gripper was opened and closed by depressing the switches located on the forward side of the ball. The translation motion envelope provided for $\pm$ 95 cm of displacement from the centerpoint along each axis, and the rotational motion envelope provided for $\pm$ 15° for roll and pitch and $\pm$ 10° for yaw. When released, the controller returned to the center location. The hand controller processing computer provided rudimentary auditory force feedback information which was proportional to the amount of force in the slave. The hand controllers were operated in a "base frame" mode. The translational axes were referenced to a universal coordinate system, while the rotations were relative to the slave arm wrist orientation.

The test articles consisted of a task board and a simulated ORU. The task board provided the operator with a group of tasks requiring a wide variety of generic manipulator activities including grasping, translation, object rotation, hand-eye coordination, and dexterity. A peg was grasped with the end effector and used to perform subsequent tasks, such as activating a series of switches and plates. Indicator lights provided feedback to the operator upon successful task execution.

The surface-mounted ORU apparatus was a 51 x 51 x 76 cm box mounted on a wooden surface by a latch on its right and left sides, which was operated by rotating a metal handle. A center handle facilitated movement of the ORU which was counterweighed with a six-DOF off-loading system to simulate zero gravity conditions.

2.1.4 Procedures - Each subject was briefed on the use of the manipulator and the specific task scenarios. Each subject was also given time to operate the manipulator and several familiarization trials for each scenario prior to any test trail. The task board scenario required grabbing the peg from a tool rack with the slave arm, executing a fixed series of operations, and returning the peg to the tool rack. The ORU task required the unlatching, removal, storage, replacement, and securing of the ORU. All tasks were performed with a single slave arm. CCTV was used, and control of camera views and functions was achieved through subject's voice command to a laboratory assistant.

The task board scenario was accomplished first. Within each type of scenario, the sequence of controller types was balanced so that half the subjects used the master controller first. Four test trials of task board and two of the ORU scenario were performed.

2.1.5 Dependent Variables - Total task length was recorded for the task board, while both total time and subtask times were recorded for the ORU task. Two measures of manipulator control quality were obtained: error frequency and test conductor's evaluation of control/efficiency. Errors were defined as inappropriate contacts between the manipulator and the test article, termination and restart of a task sequence, and dropping of a tool or test article. During the ORU task, evaluations of the test subject's control of the manipulator were made to gauge the smoothness and efficiency of control actions (e.g., to distinguish between rough jerky movements and smooth, efficient movements). A five-point scale was established on which higher scores were indications of greater control.

Operator workload was evaluated along cognitive, manual control, and physical dimensions. An overall workload assessment was obtained as well. The workload evaluations were made by test subjects following all trials within an experimental condition. The evaluations were made on five-point rating scales ranging from low to high workload. Several scale items were developed to assess each of the workload dimensions [5].

2.2 Results

2.2.1 Task Time - Performance was approximately twice as fast with the master controller for both tasks. On the task board, the mean task time was 200 and 377 seconds for the master and six-DOF controller, respectively, $F(1,5) = 17.17$, $p < 0.01$. On the ORU scenario, the mean task was 206 and 483 seconds, respectively, $F(1,5) = 7.04$, $p < 0.01$. ORU subtask times were examined to determine whether the large time differences were associated with particular activities such as long translations reflecting longer time to achieve high end effector rates, or fine manipulations (requiring greater control precision). Differences were not found to be associated with particular subtasks.

2.2.2 Manipulator Control Quality - A training effect for error reduction was observed for both control systems (Figure 1). An average error reduction of 2.3 was observed, with the greatest reduction observed between Trials 1-2 and 3-4. By Trial 4 there was no significant difference between the control systems.

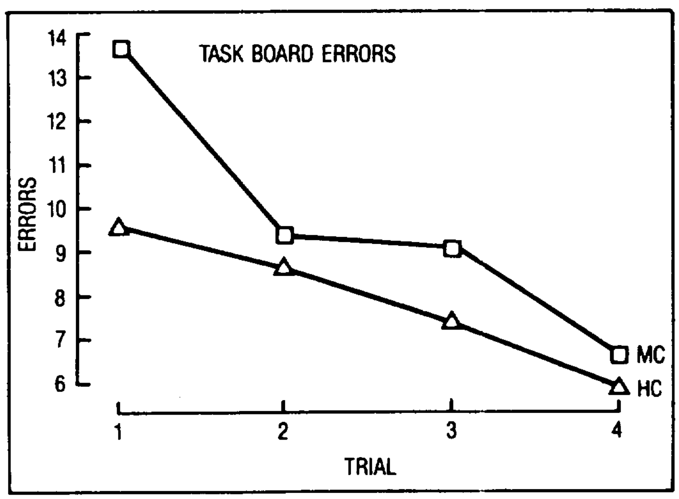

Figure 1. Task board errors as a function of controller type and trial

An additional analysis was made of the relationship between the time it took to complete the task board scenario and the number of errors made. The correlation of errors with time was significant for the hand controller (0.73, $p < 0.01$) and insignificant for the master controller (-0.27). The regression equation for predicting task board time (t) from errors (e) for the hand controllers was: $t = 31.18e + 49.09$. Errors had a major influence on time. Predicted task time with zero errors was 49 seconds. The beta weight for errors indicated that each error increased task time by approximately 31 seconds. The differential relationship between errors and time for the two control systems indicated that different control strategies were utilized.

Few errors were observed on the ORU task; hence, no statistical analysis was conducted. As with the task board scenario, more errors were made with the master controller (seven) than the hand controllers (four).

With respect to ORU control/efficiency ratings, a significant interaction was detected between control system and trial, $F\ (1,5) = 7.35,\ p < 0.05$. This interaction resulted from a slight drop in average control ratings for the master controller on Trial 2 (from 3.33 to 2.5), while no such drop occurred for the hand controller (mean of 3.33).

2.2.3 Workload - With respect to cognitive workload, three rating scale items were evaluated: attention required, decision making, and skill required. The hand controllers were generally rated higher in workload although the differences were not statistically significant. Based upon subjects' comments, the perception of higher cognitive workload of the hand controllers was based upon: (1) the relatively more complex mental transformations required to position the slave arm end effector, and (2) the absence of more informative force feedback which made decision making in problem situations very difficult.

Three rating scale items were used to evaluate manual control workload: difficulty maneuvering slave arms, difficulty manipulating end effectors, and difficulty controlling parts/equipment. The master controller was generally rated high in manual control difficulty, but again the differences were not statistically significant. Several comments made by subjects indicated that the hand controllers provided superior control in close-in situations where fine, precise movements were required. The master controllers were more difficult to control in that situation, because the force required by the operator to overcome static friction led to relatively quick, erratic movement that did not facilitate control in tight situations. However, irregular and compound axis translations were easier with the master controller.

Physical workload was assessed using three rating scale items: hand/-finger fatigue, arm fatigue, and task related body fatigue. The master controller was rated significantly higher on all comparisons but body fatigue. For hand fatigue the mean ratings were 2.66 and 1.25 for the master and six-DOF controller, respectively, $F\ (1,5) = 85,\ p < 0.001$. For arm fatigue, the mean ratings were 2.08 and 1.33 for the master and six-DOF controller, respectively, $F\ (1,5) = 10.29,\ p < 0.01$. Reasons offered by test subjects for greater fatigue of the master included the strength required to overcome static friction and infrequently used muscles.

In the evaluation of overall workload, the master controller was rated as significantly higher in workload due largely to the differences along the physical dimension. The mean ratings were 2.41 and 1.66 for the master and six-DOF controller, respectively, $F\ (1,5)\ 19.29,\ < 0.01$.

Several interesting comments were offered with regard to overall workload considerations. Concerning the value of force feedback with the master controllers, one subject made the following comment, "I started this task without force feedback and it took very long; I was concentrating so hard on the visual information that I was unaware of the absence of force feedback. When feedback was turned on, there was dramatic difference in presence, realism, and task time." The comment was made after an ORU trial was terminated because the force feedback had not been activated.

3. STUDY 2

In the second study, a truss assembly task representative of the kind anticipated for Space Station was performed. This task was an excellent scenario for evaluating teleoperator control because it required simultaneous operation of both manipulator arms and complex multiaxis slave arm movements.

3.1 Methods

3.1.1 Participants - Six engineers participated in this study. One had extensive experience with master-slave manipulators and a second was familiar with hand controllers. The other four had varying degrees of familiarity with teleoperator manipulator systems, but none were experienced with hands-on operators.

3.1.2 Experimental Design - Two within-subjects factors were investigated: (1) controllers having two levels (master controllers and six-DOF hand controllers); (2) truss strut alignment having three levels (vertical, diagonal, horizontal). Each alignment was thought to represent different problems for the operator. A third factor was investigated in the study, end effector gripper type, but its effect did not impact on the comparison of control systems, so it is not discussed in this paper. Details can be found elsewhere [6].

3.1.3 The Laboratory and Test Equipment - The laboratory and test set-up was essentially the same as for Study 1. Differences included the positioning of cameras at the telerobot and the test article. Cameras were positioned in the center of the slave arms below the shoulder joint and at a 45° angle from the left and right shoulders. The truss structure apparatus was composed of three struts: battens and a diagonal; a truss node mounted to the board on a wooden block, a vertical support board, metal clips attached to the board to retain stowed struts; and three strut-connectors (attached to the node). A sleeve on the strut was moved toward the node and rotated about the strut's longitudinal axis approximately 90° to lock. The orientation of the truss struts was vertical, horizontal, and diagonal with respect to the orientation of the telerobot.

3.1.4 Procedures - Each subject was briefed on the use of the manipulator and was given time to assemble struts for familiarization. During the test, the truss was assembled twice with each control system. The order with which the control systems were used was balanced across subjects. All scenarios were completed with a strut assembly sequence of vertical, diagonal, and horizontal. As in the first study, only CCTV views were used and cameras were voice-command controlled.

3.1.5 Dependent Variables - The dependent variables used in the study were the same as used in Study 1, with one exception: no assessment of errors was made.

3.2 Results

3.2.1 Task Time - Total assembly of all three struts took significantly longer with the hand controllers (1.598 seconds) than with the master controllers (691 seconds), $F (1,5) = 52.82$, $p < 0.001$. An examination of assembly times for individual struts indicated that the master controllers were associated with faster performance for all struts.

3.2.2 Manipulator Control Quality - Test conductor's ratings of the control/efficiency of slave arm movements indicated slightly higher evaluations for the master controllers than for the hand controllers across all three individual strut assemblies, but the difference was not statistically significant.

3.2.3 Workload - Data for all workload variables are presented in Table 1. Cognitive workload was evaluated with the four-scale items presented in Table 1. The hand controllers were rated significantly higher in cognitive workload than the master controllers. Many of the comments offered by test subjects indicated that the hand controllers required much greater mental effort to operate than the master controllers, which were judged to provide more natural control. Since the task required the simultaneous control over two slave arms, the determination of appropriate control inputs was cognitively demanding. This can be readily understood, since the two-arm tasks often required a different input to each controller depending on the orientation of the end effector. In addition, the availability of force reflection in the master arm controllers was an aid to decision making which was absent for the hand controllers.

Manual Control was evaluated using the three-scale items indicated in Table 1. The hand controllers were rated significantly greater in workload for both end effector and equipment control. Comments from the test subjects indicated that the hand controllers were more difficult to use when operating in situations where axes were coupled. This was especially problematic in assembling the diagonal strut, where Y and Z axes were necessarily coupled. With the master controller, these motions were more easily accomplished.

Physical workload was evaluated using the three scale items indicated in Table 1. The master arm controllers were significantly more fatiguing than the hand controllers for arm and hand fatigue, but not for overall body fatigue.

The subjects' assessments of total workload is also provided in Table 1. Interestingly, no significant differences between the control systems was observed. The greater cognitive and manual control workload associated with hand controllers was probably offset by the greater physical workload of the master controllers. This observation illustrates the importance of evaluating individual workload dimensions rather than relying on a single global assessment.

4. CONCLUSIONS

Several consistent patterns were observed across both studies. The time to complete the task scenarios was approximately twice as long with the hand controllers as with the master controllers. The trend toward higher cognitive workload of the cognitive workload of the hand controller observed in Study 1 was confirmed in Study 2. The cognitive complexity of controlling the telerobot with the hand controller became a significant problem when two slave arms were operated simultaneously. Greater physical workload of the master controllers was also found in both studies.

Table 1. Ratings for Workload Variables

VARIABLE	CONTROLLER TYPE: MASTER M[1]	MASTER SD[2]	HAND M[1]	HAND SD[2]	F STATISTIC
COGNITIVE					
Attention	3.00	0.63	3.58	0.61	8.45[3]
Decision-Making	2.58	0.45	3.41	0.62	11.36[3]
Manipulator Skill	2.50	0.54	3.75	0.45	25.00[4]
Task Skill	2.75	0.47	3.33	0.51	14.41[3]
MAN. CONTROL					
Slave Arm	1.91	0.70	2.41	0.68	14.42[3]
End Effector	2.00	0.88	3.16	0.69	49.00[4]
Equipment	2.25	0.78	3.41	0.48	2.50
PHYSICAL					
Hand Fatigue	3.00	1.25	1.08	0.24	24.00[4]
Arm Fatigue	2.58	1.09	1.25	0.47	11.03[3]
Overall Fatigue	2.16	1.16	1.41	0.86	3.85
TOTAL WORKLOAD	2.41	1.10	2.83	1.07	1.40

Notes:

1 Average Rating (Higher values = higher workload)
2 Standard Deviation
3 F Statistic is significant at the $p < 0.05$ level
4 F Statistic is significant at the $p < 0.01$ level
Degrees of Freedom = (1,5)

The major advantages of the master replica controllers were their ability to accomplish tasks more quickly and their "naturalness" of control. The latter was especially true when complex multiaxis inputs were required. Their major disadvantages were less control over sustained movements requiring very fine, precise control, and high operator physical workload/fatigue. The major advantages of the hand controllers were the control that could be achieved over precision movements, and very low physical workload. The major disadvantage of hand controllers was the cognitive complexity of correlating control inputs with slave arm outputs, especially when the operator was coordinating movements of two manipulator arms with the end effectors in different orientations. Further, no simple solution can be implemented, such as altering the coordinate reference frame, as is done with single manipulator arm systems, or using an end-effector mode similar to that of the Shuttle RMS. With a two-arm telerobot, each arm would have an independent end-effector mode, which would require two separate camera views. This would make simultaneous control of both arms difficult.

Several improvements to the present hand controller design and implementation are being studied. First, the auditory-force feedback was not sufficiently informative to the operators. Providing force reflection to the controller itself, or a force/torque graphic display is being investigated. Second, alternative rate and position control options will be made available to the operator. Third, alternative controller displacement-rate functions such as variable slope (providing a fine to course gradient), exponential, or linear-linear "dog-leg" are being investigated.

5. ACKNOWLEDGEMENT

Portions of this work were supported by NASA, contract (NAS 9-17229). Appreciation is expressed to Lyle Jenkins, NASA Technical Monitor, for his assistance. The opinions expressed are those of the authors alone and not necessarily NASA, or the Grumman Corporation.

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